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The Electron Cooling Project: Commissioning of a MW-range, DC beam generator

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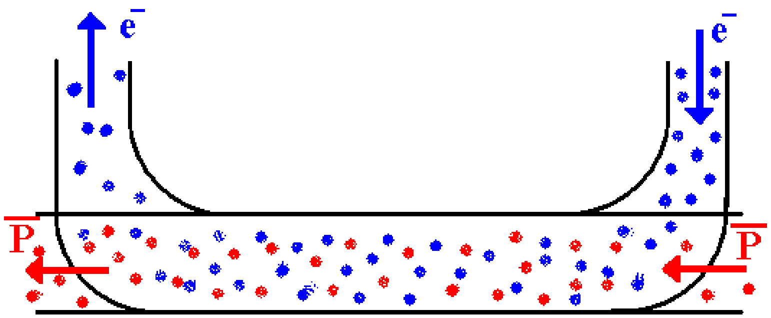
- The Recycler Electron Cooling Project and the scheme of beam generation
- High voltage
- Beam current and stability of operation
- Summary

The goal of the electron cooling in the Recycler is to increase an effective antiproton flux by a factor of two or more by means of a cooling- stacking process.



The main idea of the electron cooling is a heat exchange through Coulomb scattering between a hot antiproton and a cold electron beams while they are mixed in an cooling section.

Design electron beam parameters in the cooling section

Energy	4.3	MeV
Current (DC)	0.5	A
$\Delta p/p$	$\leq 1\cdot 10^{-4}$	
$p_\perp/p$	$\leq 1\cdot 10^{-4}$	
Beam radius	5	mm
Cooling section length	20	m
Magnetic field	50-150	G

Restrictions for a beam generation system at energies of the cooling beam $\geqslant$1 MeV:

- because of the high beam power, an energy recovering scheme or a multiple beam pass through the cooling section is necessary;

- an optimum focusing in the cooling section is solenoidal;

- the cathode should be immersed into a longitudinal magnetic field to match the magnetic flux through the beam in the cooling section.

Various options for beam generation:

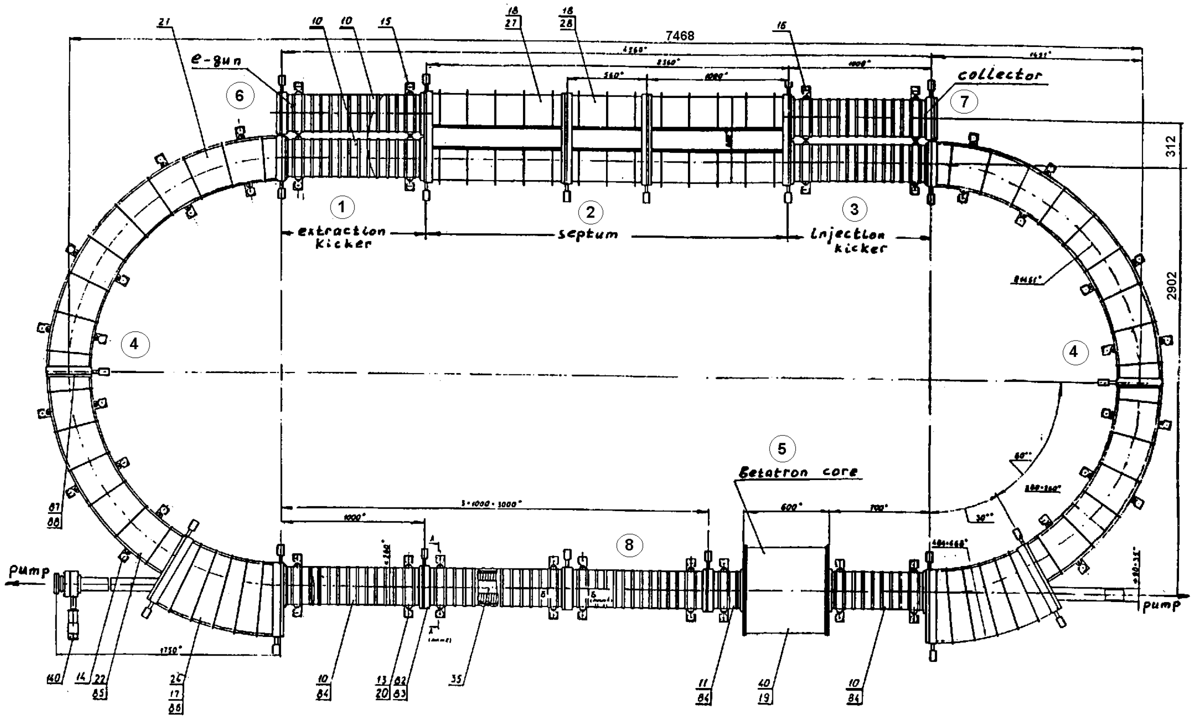
- cooling by a multi-pass electron beam system;

- a linac with energy recovery;

- an electrostatic scheme.

Which one is the least risky?

Multi-turn acceleration and cooling



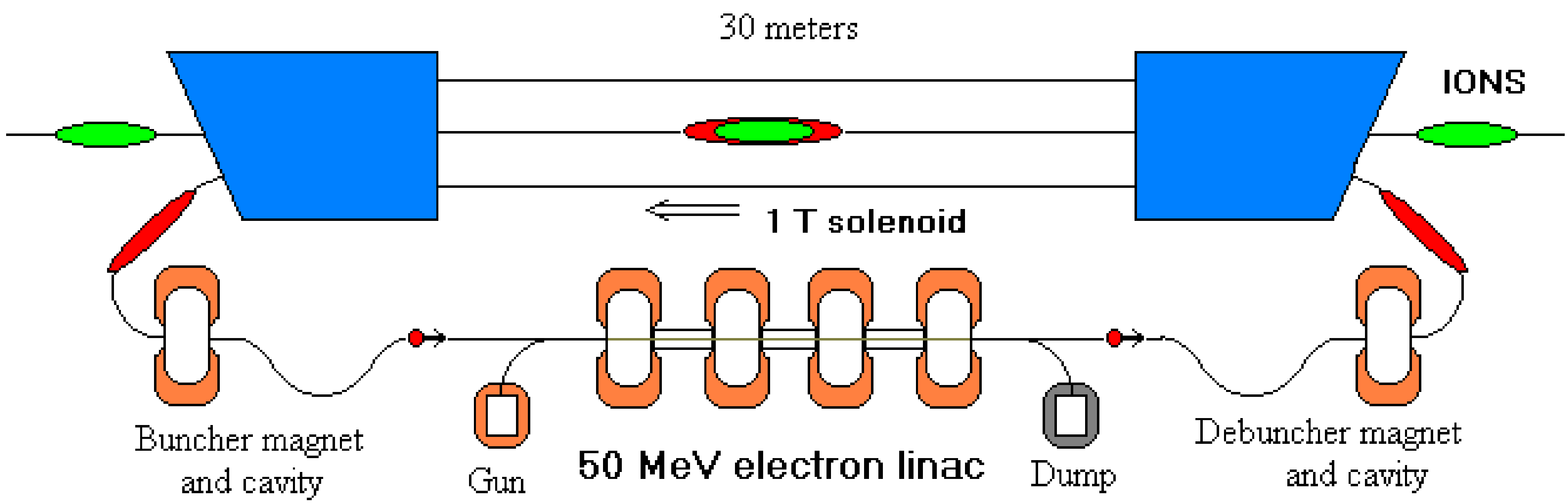
Modified betatron
(G.Jackson, 1997)

Project MOBY
(I.Meshkov et al.,
JINR, Russia)

- might be the cheapest way;
- electron temperature due to beam instabilities and IBS seems to be high.

Linac with energy recovery

- a proven technology of Ampere-range beam acceleration at multi-MeV energies
- presumably, the best technology for electron cooling in colliders
- $\Delta p/p \sim 10^{-4}$ has not been demonstrated



A schematic diagram of the proposed RHIC electron cooling system (I. Ben-Zvi et al., 2001). I_{peak} ~10 A, <I> ~ 0.1 A, $W_{e^-cooling}$= 50 MeV, E_{damp}~ 1MeV.

Electrostatic scheme

- the best beam quality
- in principle, the electron energy can be up to 25 MeV (the world highest potential in an electrostatic accelerator, Oak Ridge tandem built by NEC*, 1985)
- all existing electron cooling systems are electrostatic with the maximum energy of 300 keV

Parameters achieved on some of electrostatic accelerator-based recirculation systems

System	Energy MeV	Beam Current A	Pulse duration	Rel. current losses
UCSB (vertical)	6	2	20 μs	$3 \cdot 10^{-3}$
UCSB (horiz.)	2	2	5 ms	$3 \cdot 10^{-4}$
BINP (1986)	1	1	8 hours	$1 \cdot 10^{-3}$
FNAL/NEC/UW test (1989)	2	0.1	DC, <10 min	$1 \cdot 10^{-4}$
FNAL/NEC (1999)	1.2	0.2 0.9	5 hours seconds	$5 \cdot 10^{-6}$ $1 \cdot 10^{-5}$
FNAL(2001)	3.5	0.5 0.7	1 hour minute	$1 \cdot 10^{-5}$ $2 \cdot 10^{-5}$

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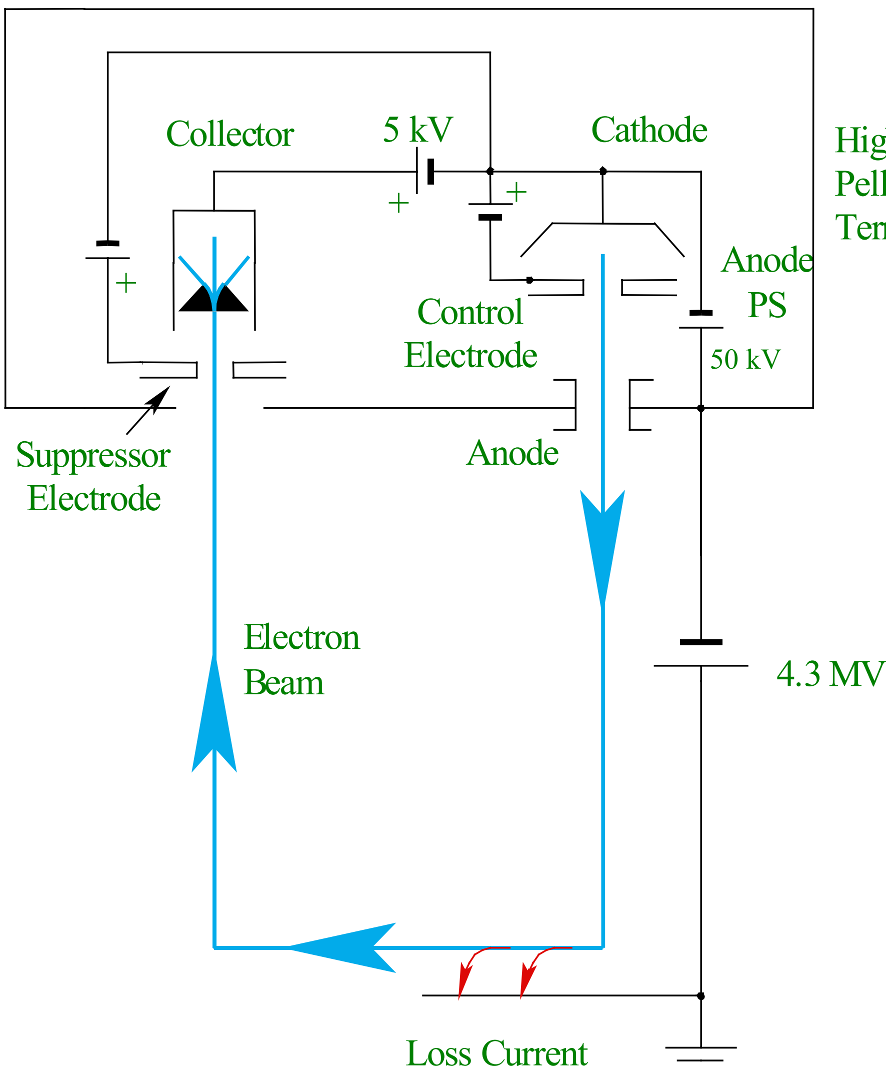
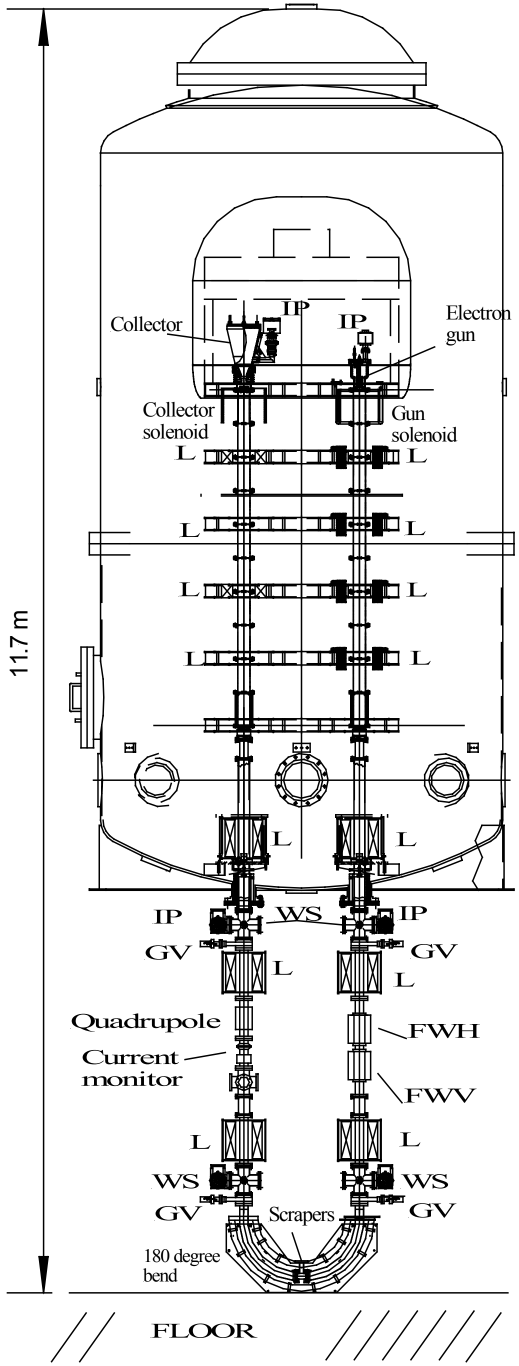
* National Electrostatics Corporation, Middlton, WI

Simplified electrical schematic of the electron beam recirculation system.



For I= 0.5 A, ΔI= 5 μA:

- Beam power 2.15 MW
- Current loss power 21.5 W
- Power dissipated in collector 2.5 kW

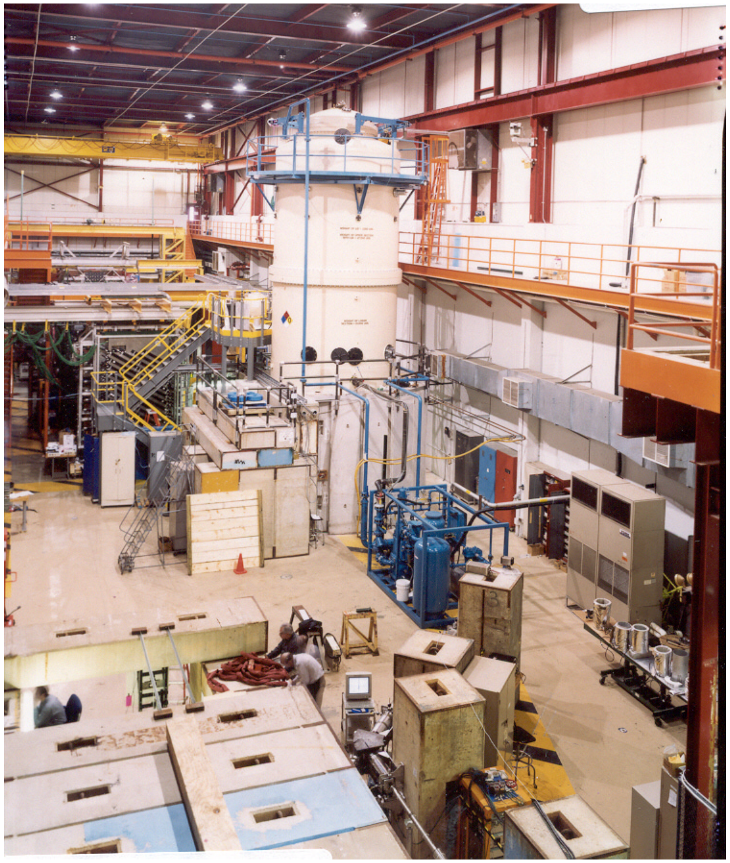


Electron beam recirculation test design parameters

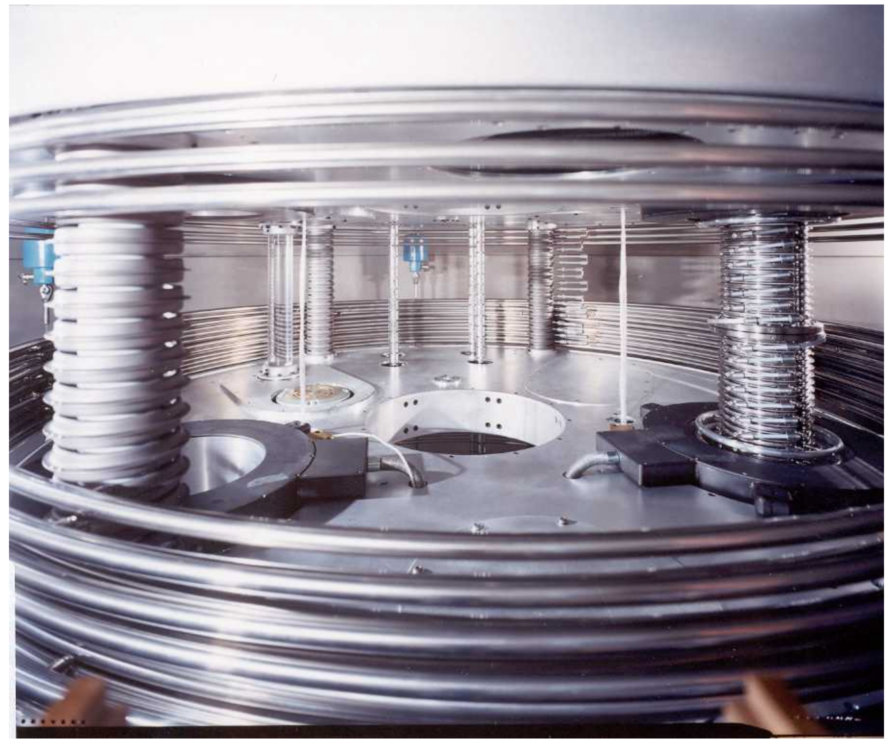
Beam current	0.5	A
Electron kinetic energy	4.36	MeV
Energy fluctuations (FWHM)	500	eV
Typical time between crashes	>1	hour
Crash recovery time	< 5	min
Magnetic field on the cathode	200-600	G

- IP- ion pump, L- solenoidal lens, GV- gate valve, WS- wire scanner, FWH and FWV- flying wires.

Fermilab Electron Cooling R&D Facility

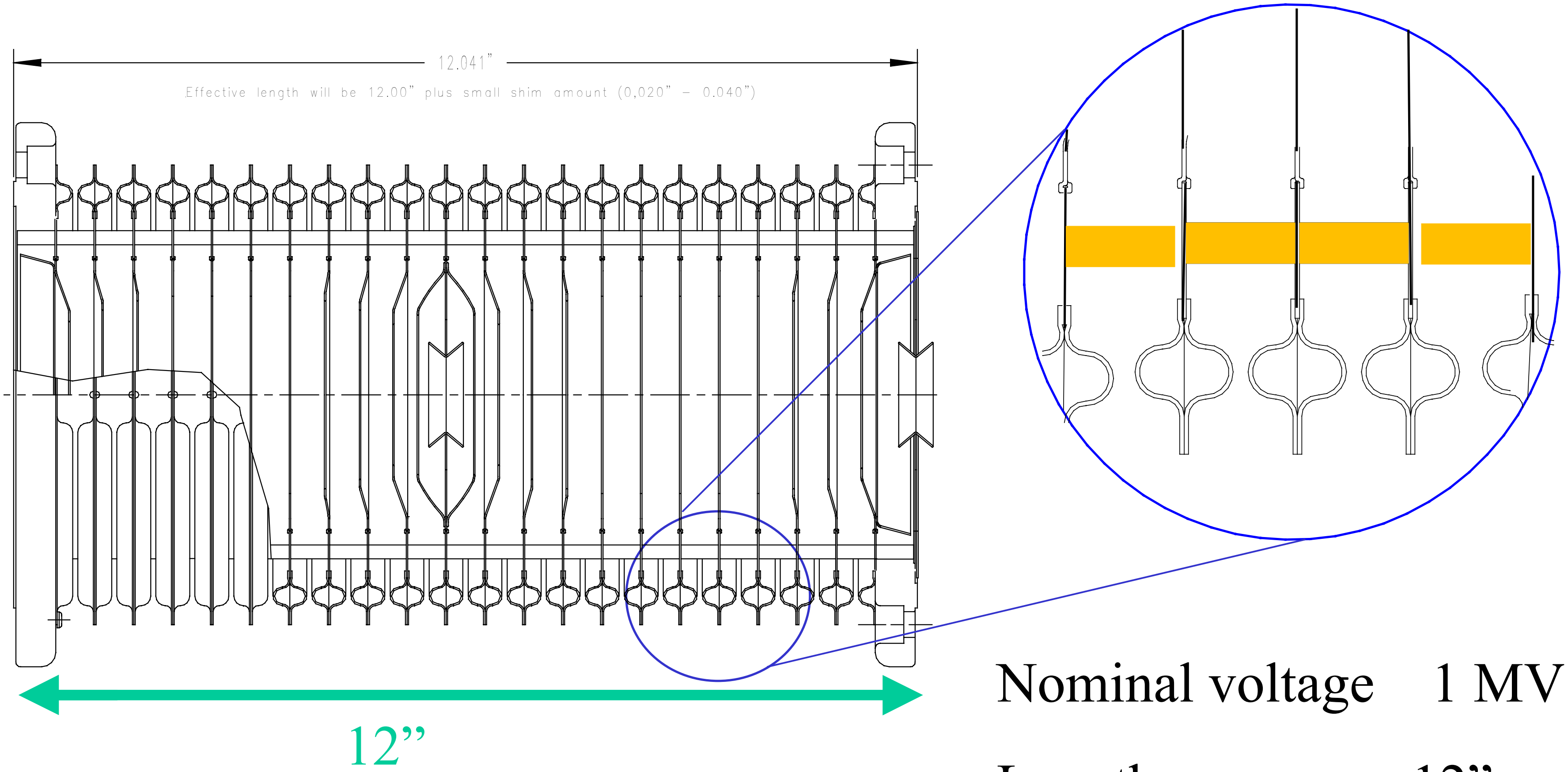


5 MV Pelletron



High-voltage column with grading hoops partially removed to show the accelerating tube (right) and the charging chains (far center).

Acceleration tube section (produced by NEC)

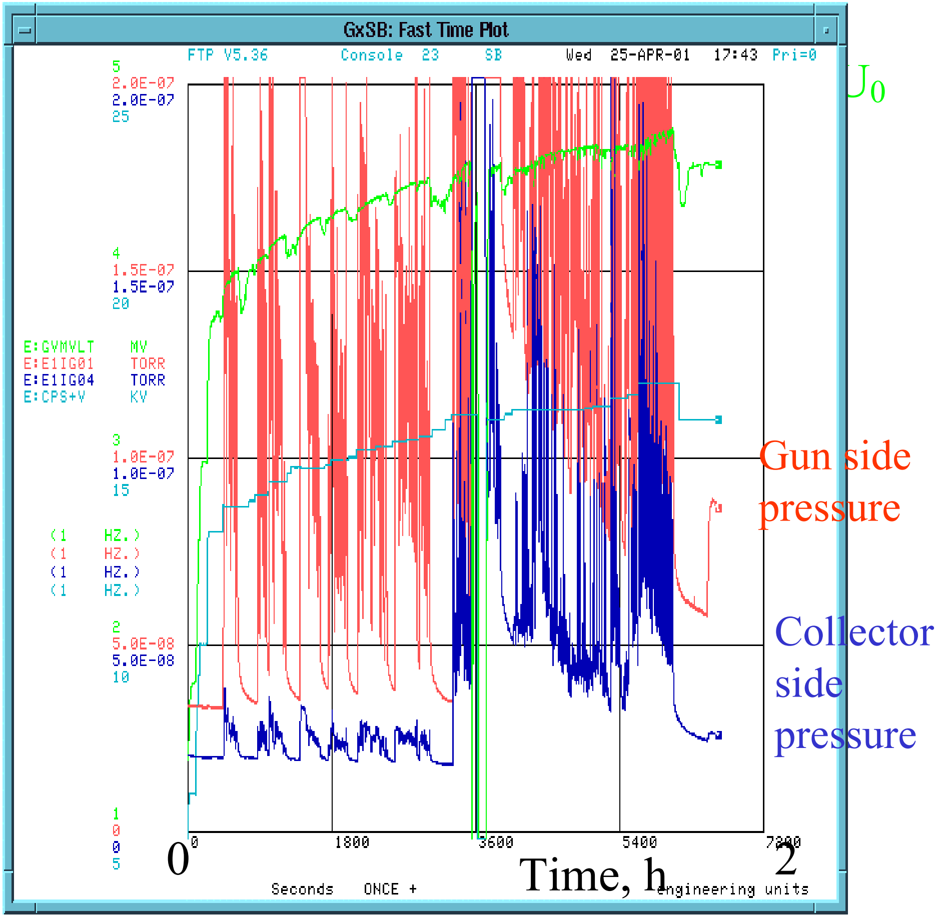


Nominal voltage 1 MV

Length 12”

Min. electrode ID 1”

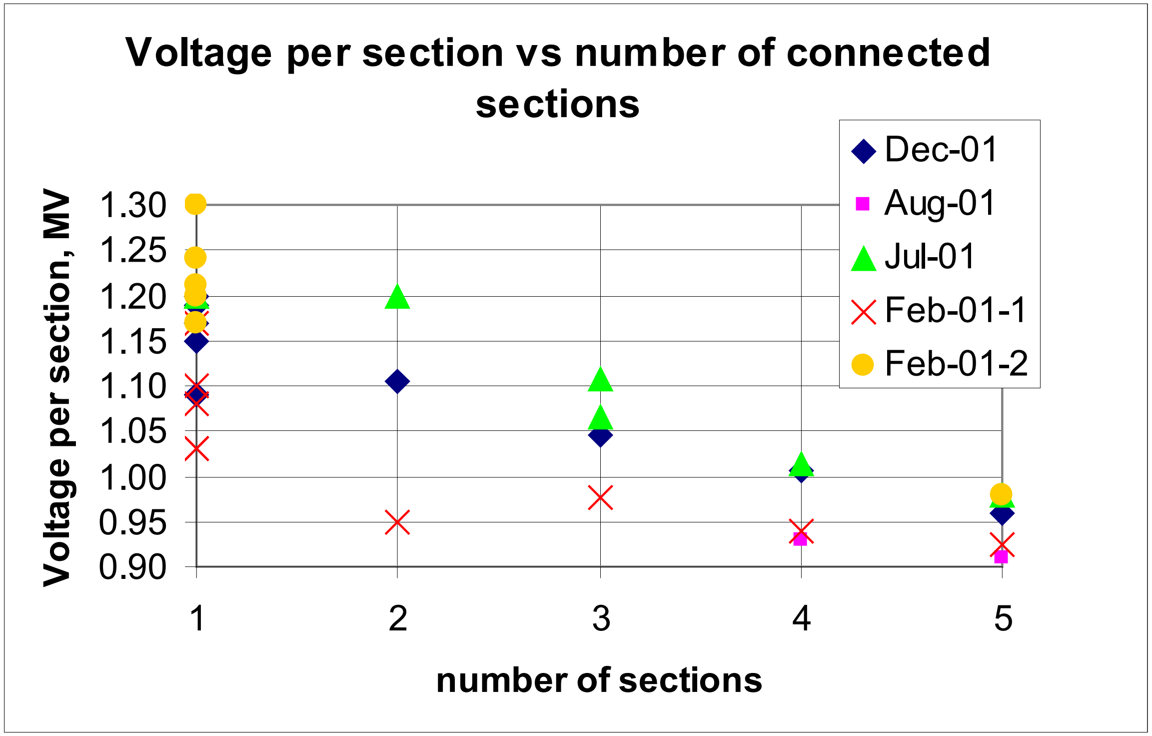
Tube conditioning



Tube conditioning after exposing the gun tube to atmosphere.

Because of the large amount of energy (3 kJ) stored in the HV terminal and its potential for damage, HV conditioning of vacuum tubes was initially performed with the help of shorting rods, one 1-MV section at a time. Each section (out of 5) was conditioned separately to 1.2 MV. The Pelletron with tubes was then conditioned to 4.5 MV. After exposing a tube to atmosphere, conditioning can be done with all tubes connected.

High voltage limitations

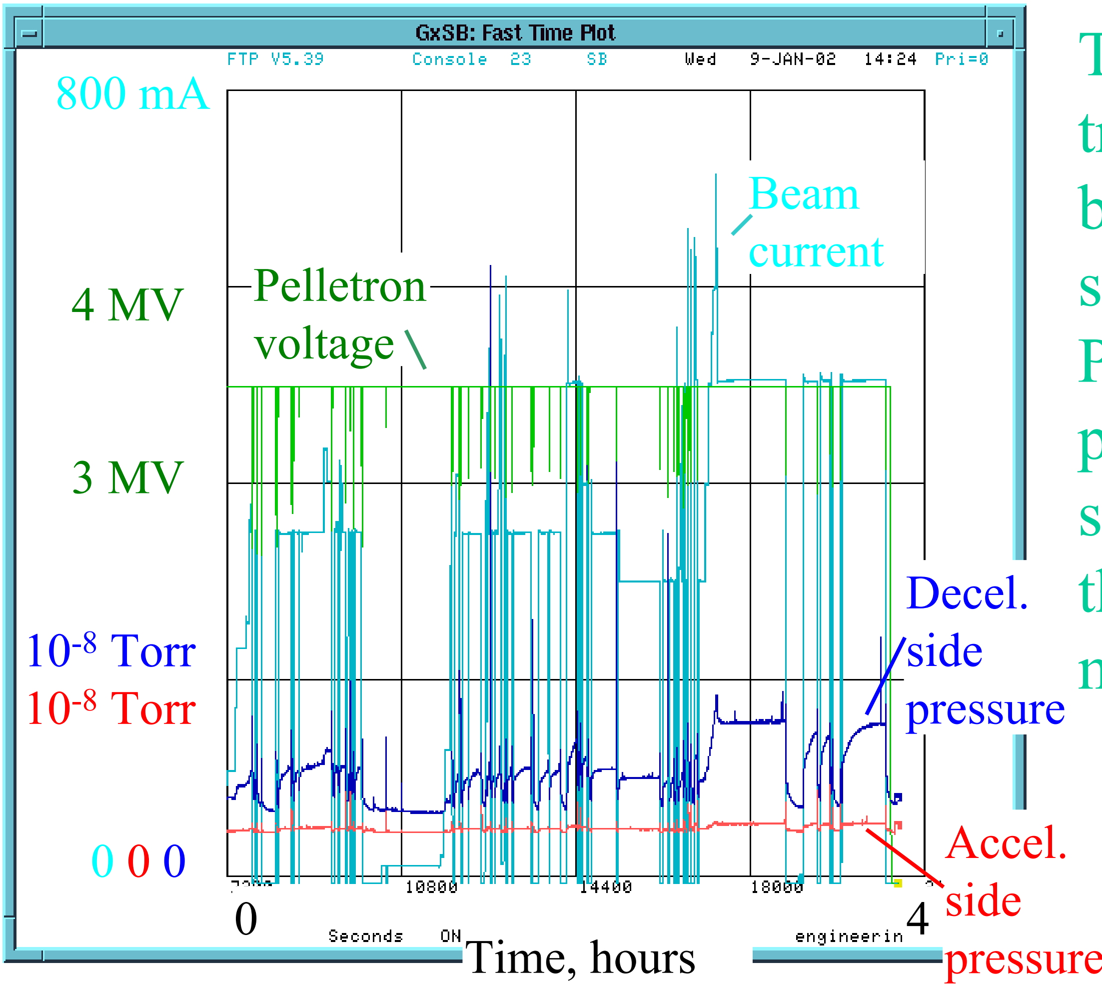


Maximum stable voltage increases non-linearly with the number of acceleration tube sections.

Most of full discharges have a detrimental effect on the tube conditioning, when the number of connected sections is more than two.

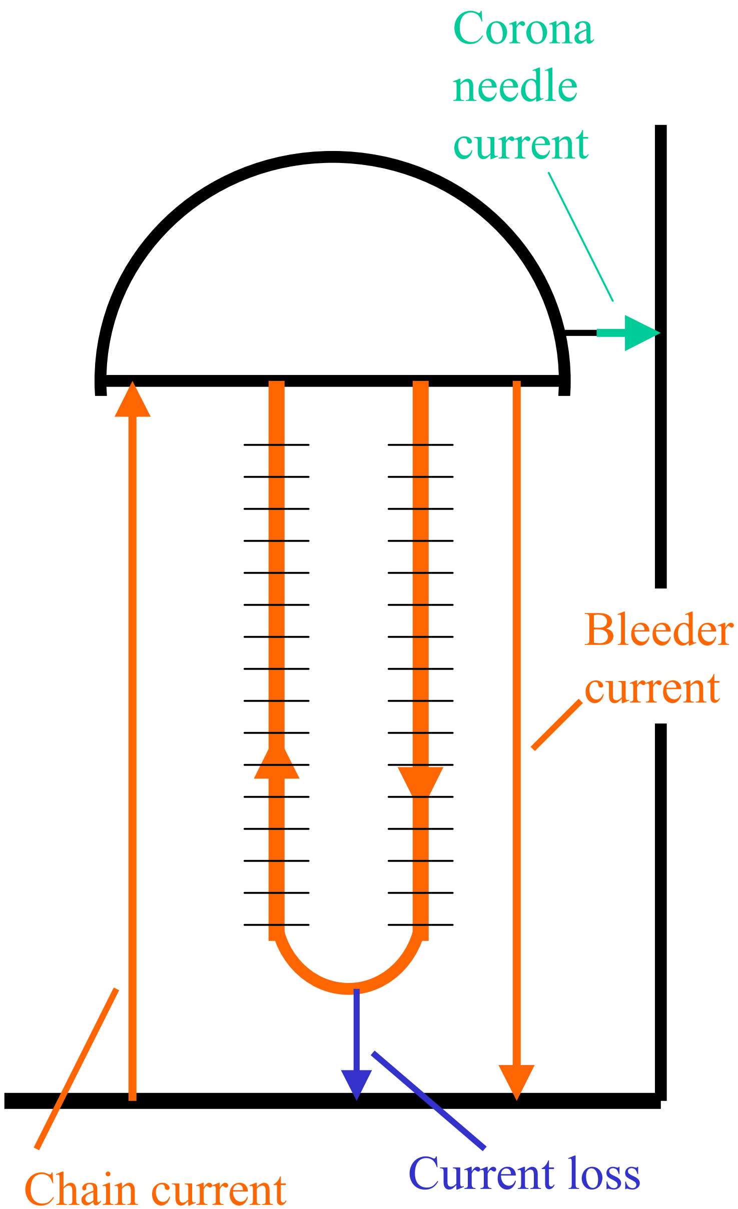
Multiple full discharges occurring during work with all sections result in a decrease of the maximum stable voltage down to ~3.8 MV, and it takes several hours to condition tubes back to the nominal voltage of 4.3 MV. That's why most of work was done at the energy of 3.5 MeV.

Pelletron "crash"



The "Crash" is a transition from a stable beam recirculation to a state with a low Pelletron voltage. The protection system switches the beam off if the voltage drops by more than 50 kV.

Beam current, Pelletron voltage, and vacuum during 4 hours of operation



Possible reasons for crashes:

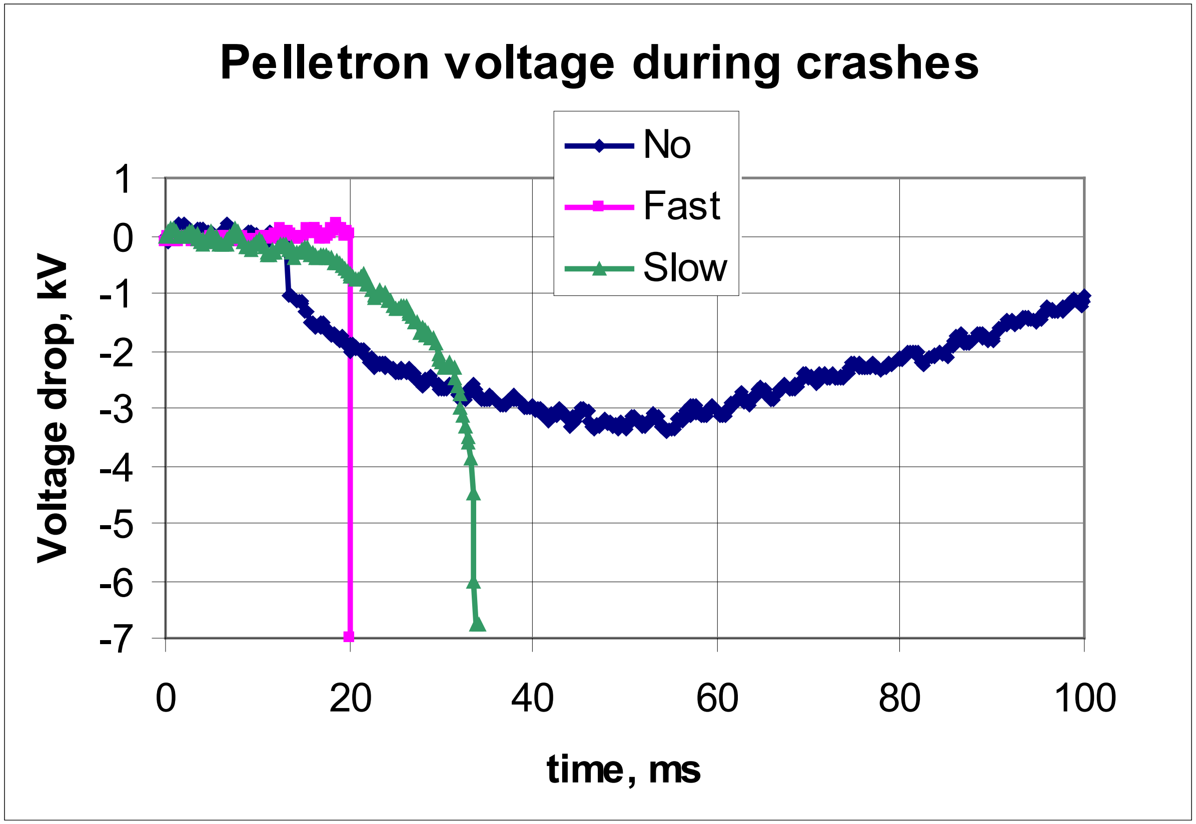
1. The current loss exceeds the regulation capability.

It occurs while one steers the beam or increases the beam current. Typically, such crashes are slow.

2. Partial discharges.

A charge, deposited to the tube ceramic by lost electrons, is removed by a discharge of a portion of the tube. Such a partial discharge results in changes in the beam envelope and position that, in turn, can increase losses and decrease the voltage further .

“Fast” and “slow” crashes

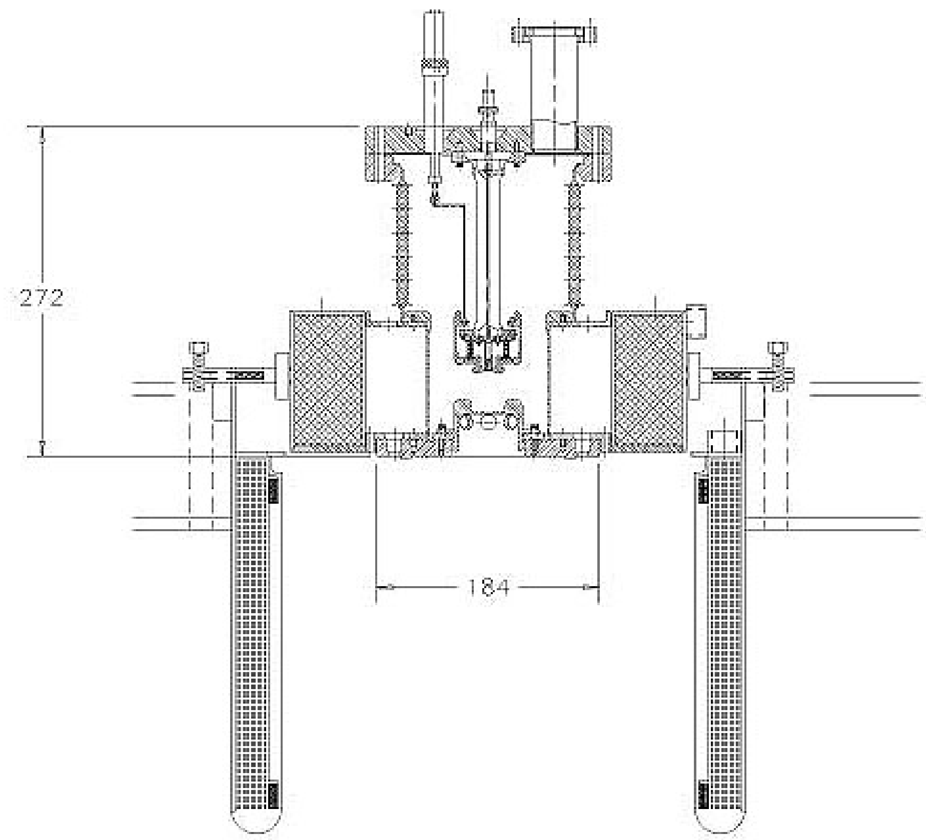


Current flowing from the terminal in a crash:

fast: >10 mA

slow: 10 - 300 μA

Charging of the tube ceramic by secondary particles



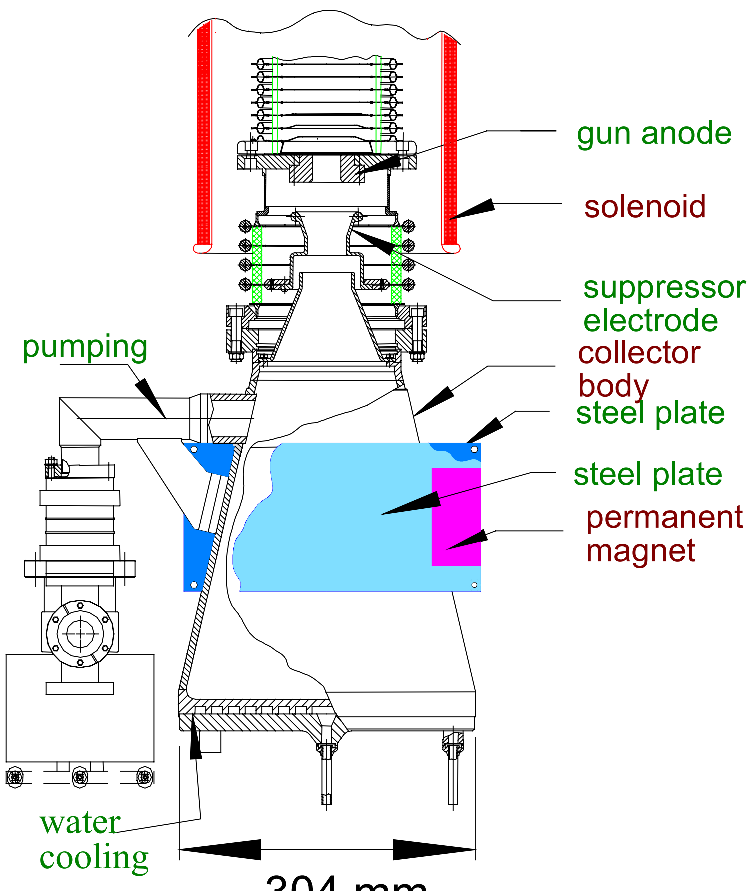
Gun assembly with solenoids

1. Halo electrons from the gun.

A solution was found in the recirculation experiment at NEC. It is a combination of a negative potential on the gun control electrode and a diaphragm in the gun anode.

Recently, a copper tip of a control electrode was replaced by a tantalum one to suppress a “dark” current that had appeared after crashes.

Charging of the tube ceramic by secondary particles



Mechanical schematic of the electron collector with transverse magnetic

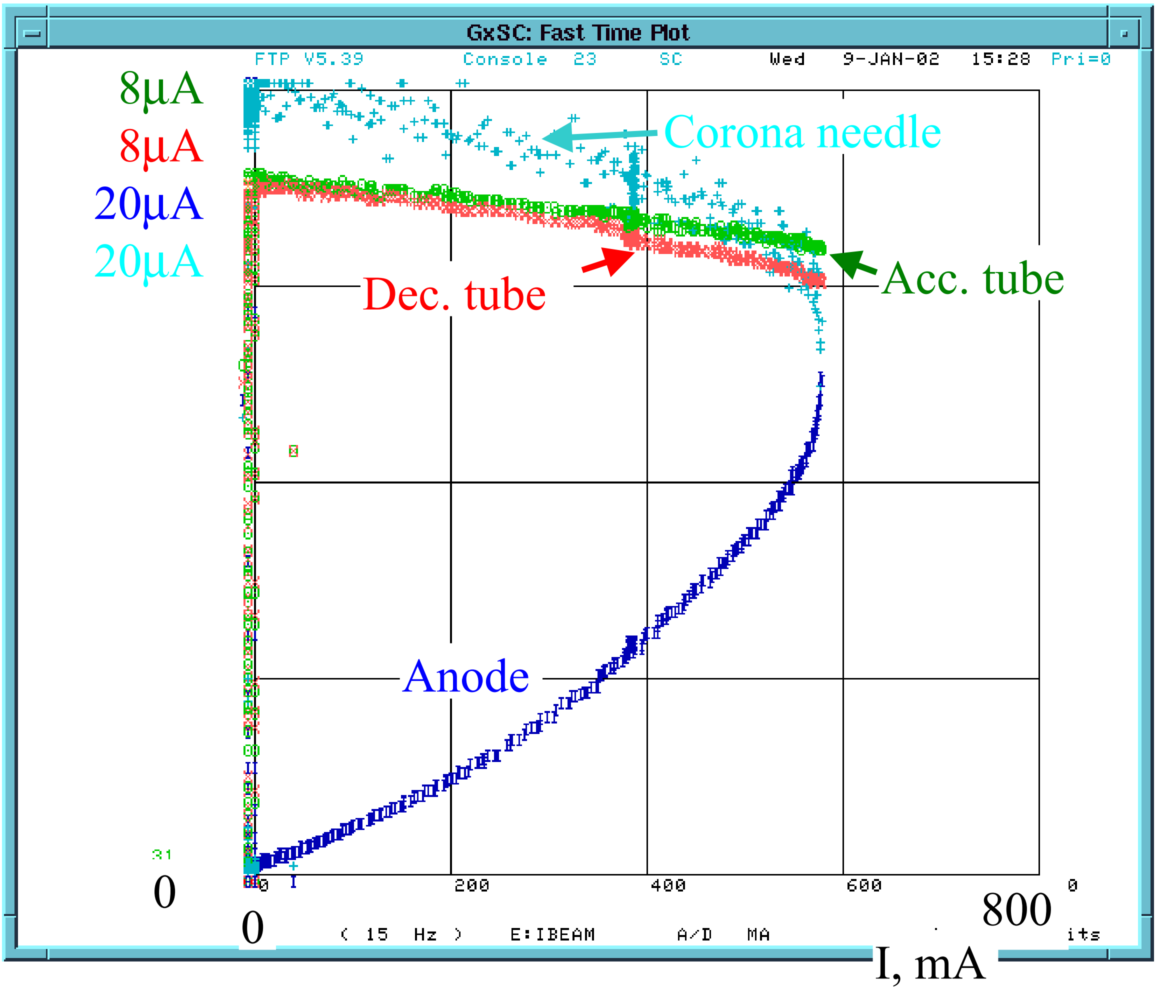
2. Secondary electrons from the collector.

On the test bench, the collector demonstrated losses below 6 μA at beam currents of up to 1.7 A.

In measurements with a 3.5 MeV beam at I = 0.5 A:

$dI_a = 8\ \mu A$,
$dI_{pelletron} = 4\ \mu A$,
$dI_{tube} = 0.5\ \mu A$

Current losses at optimum tuning



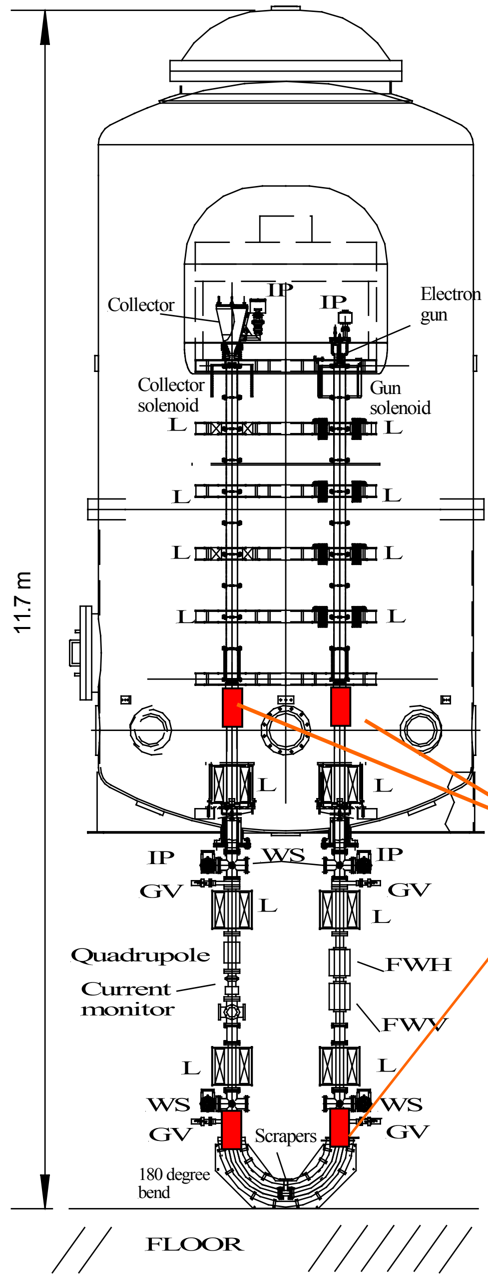
U_0= 3.5 MV

U_a= 25 kV

B_{cath} = 140 G

U_{col}= 4.5 kV

Charging of the tube ceramic by secondary particles



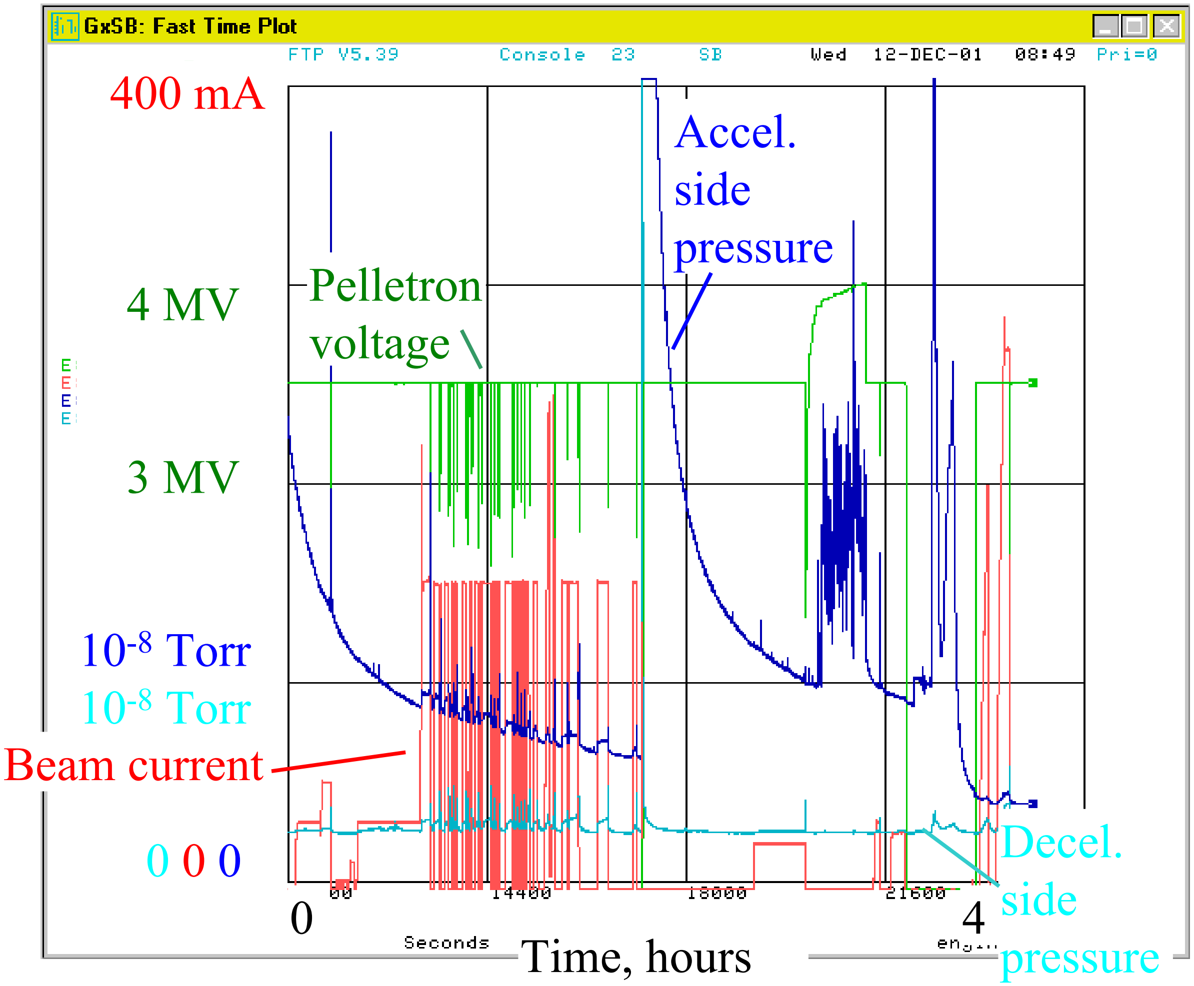
Plates used to block and clear ions

3. Ions, created by beam.

Ions originated in the beam channel can be prevented from going into accelerating tubes by a small (20-80 V) on electrodes, placed below the tubes.

A dramatic dependence of the crash frequency on the voltage was found at beam currents above 10 mA.

“Neutral” and “bad” crashes



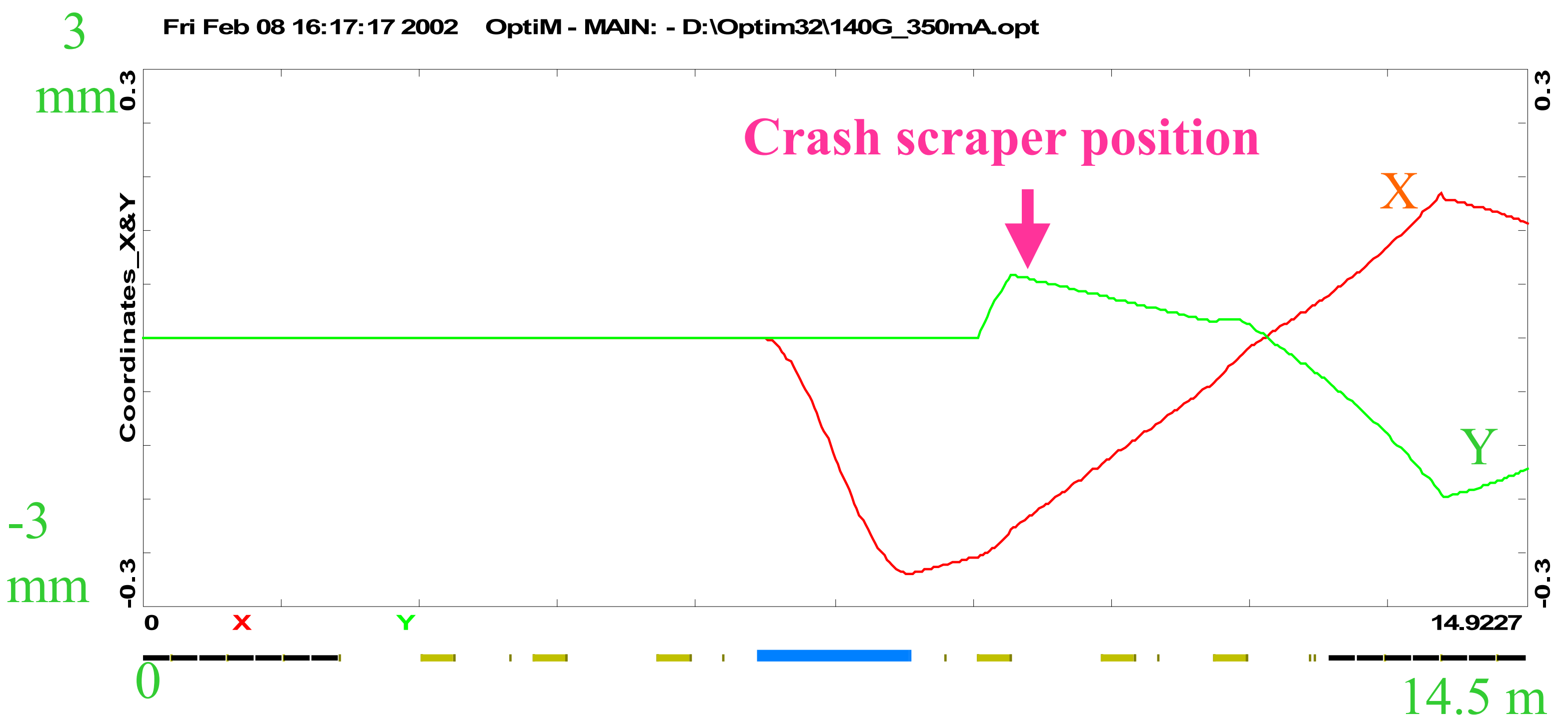
Beam current, Pelletron voltage, and vacuum during 4 hours of operation

“Neutral” crash: may be a slow voltage decrease; no dramatic changes in vacuum; the beam can be restored into its previous state in a minute.

“Bad” crash: always a fast and deep drop of voltage; the pressure increases up to 10^{-6} Torr; the time to restore a full- current beam is ~ 30 min.

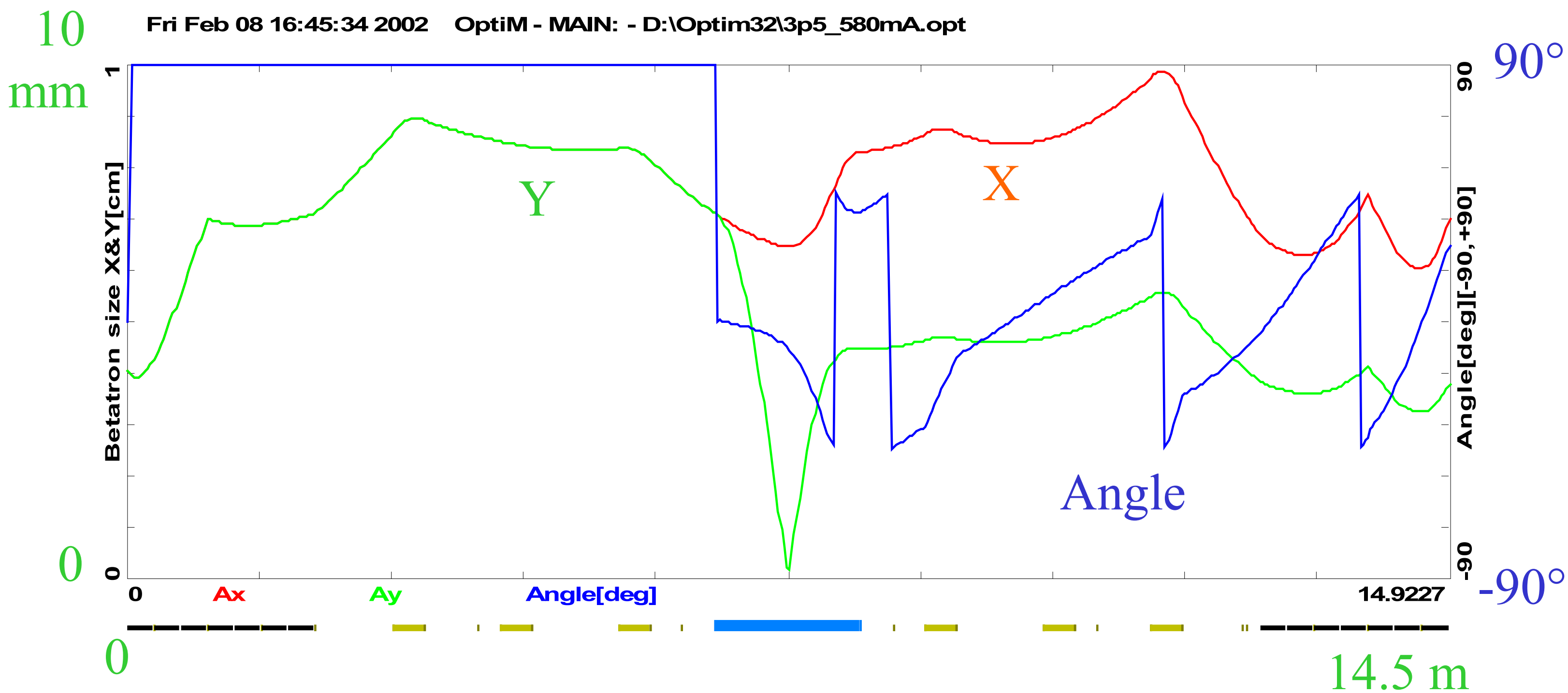
A way to prevent bad crashes: a crash scraper

When the beam energy decreases during the crash, the beam should first touch a scraper but not to the deceleration tube electrodes.



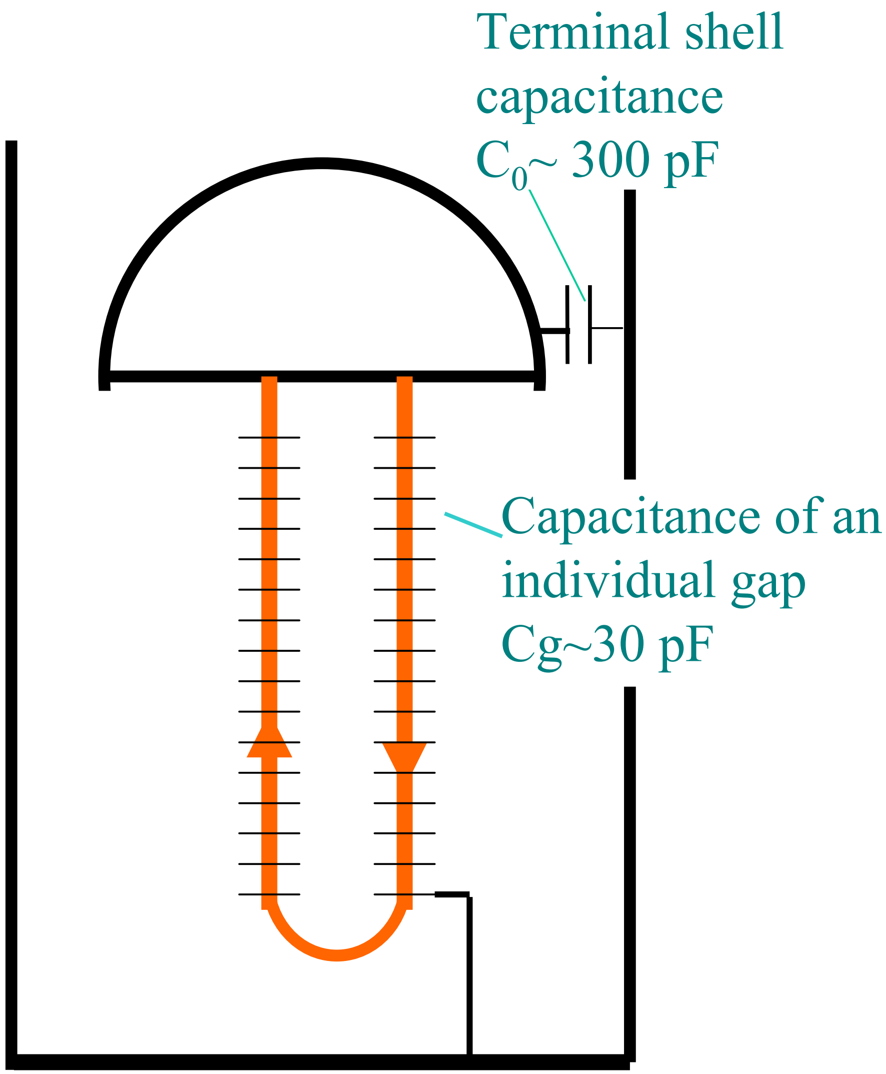
Displacement of the central trajectory when the energy decreases by 10 keV. U_0= 3.5 MV. Simulation by OptiM32.

Possible reasons for bad crashes in the acceleration tube: modification of the beam envelope during a partial discharge; overvoltage in tubes at the time of discharge



Example of a beam envelope for U_0= 3.5 MV, I = 0.57 A, B_{cath}=600 G. Simulation by OPTIM32.

Possible remedy: a large dispersion near the crash scraper and stability of the beam size in the tubes



Because $C_0 >> C_g$, sparking of a 175-kV tube section can result in a terminal voltage drop as low as 1 kV.

The ideal situation: the beam size changes caused by a potential redistribution during the crash are so small that the beam never touches the tube electrodes but rather comes to the crash scraper.

What determines the beam size in the tubes?

1. Angular momentum dominated beam

Beam envelope outside solenoids is determined by a large emittance-like contribution from the angular momentum

$$\varepsilon_N = eBr_c^2 /(2mc^2).$$

For $B = 600$ G, $r_c = 0.25$ cm, $\varepsilon_N \approx 100$ mm-mrad while the thermal emittance is by ~ 50 times lower.

2. The minimum distance between focusing elements in tubes is determined by the Pelletron's mechanical structure.

Current results

$W = 3.525$ MeV

$B_{cath} = 140$ G $I_{max} = 750$ mA (restricted by present “Beam Permit”)

$I = 500$ mA stayed for 1 h

$B_{cath} = 650$ G $I_{max} = 400$ mA

$I = 120$ mA stayed for 1 h

$W = 4.34$ MeV $B_{cath} = 140$ G $I_{max} = 400$ mA

What one needs in order to have a stable several MeV, Ampere- range, DC electron beam

1. Acceleration tubes which strength does not drop below nominal value after crashes. Current tubes are supposed to be replaced or extended.

2. Halo-free electron gun.

3. Electron beam collector with a very low back flow of electrons.

4. Electrodes blocking and clearing ions in the beam channel.

5. Vacuum in the tubes of $\sim 10^{-9}$ Torr.

6. A crash scraper.

7. A focusing system that keeps the beam far from tube electrodes even during crashes and has a large dispersion near the crash scraper.

Miscellaneous issues

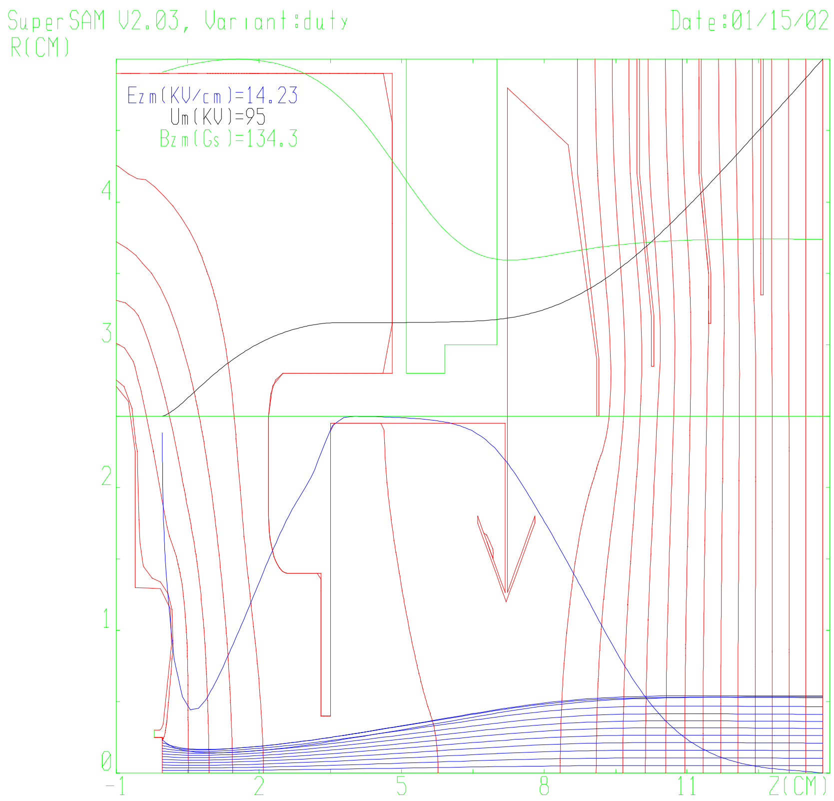
1. Reliability of electronics (G. Saewert). After August ‘01 we had no major problems with electronics itself.

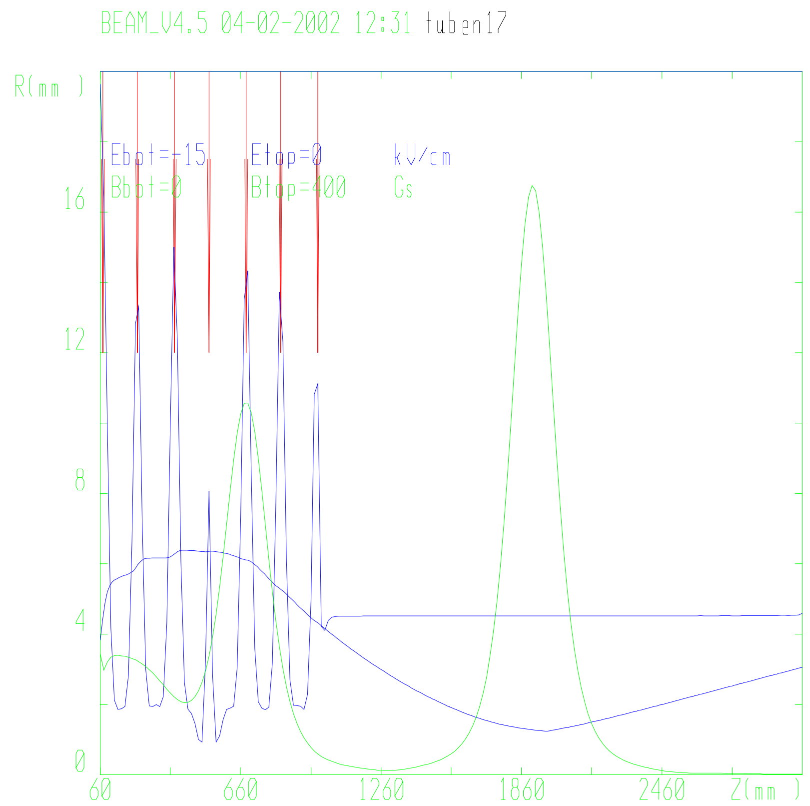
2. Spark- and beam-protection: fast (hardware) gun shut-off; software gun shut-off; improving of a mechanical design of various elements

3. Beam simulation: gun (SSAM) + low-energy part of acceleration tube (BEAM) + high-energy part (OptiM32). We have only estimations for the beam envelope in the low-energy part of the deceleration tube and in the collector.

4. Beam measurements: wire scanners, beam scrapers, BPMs. A flying wire is under commissioning.

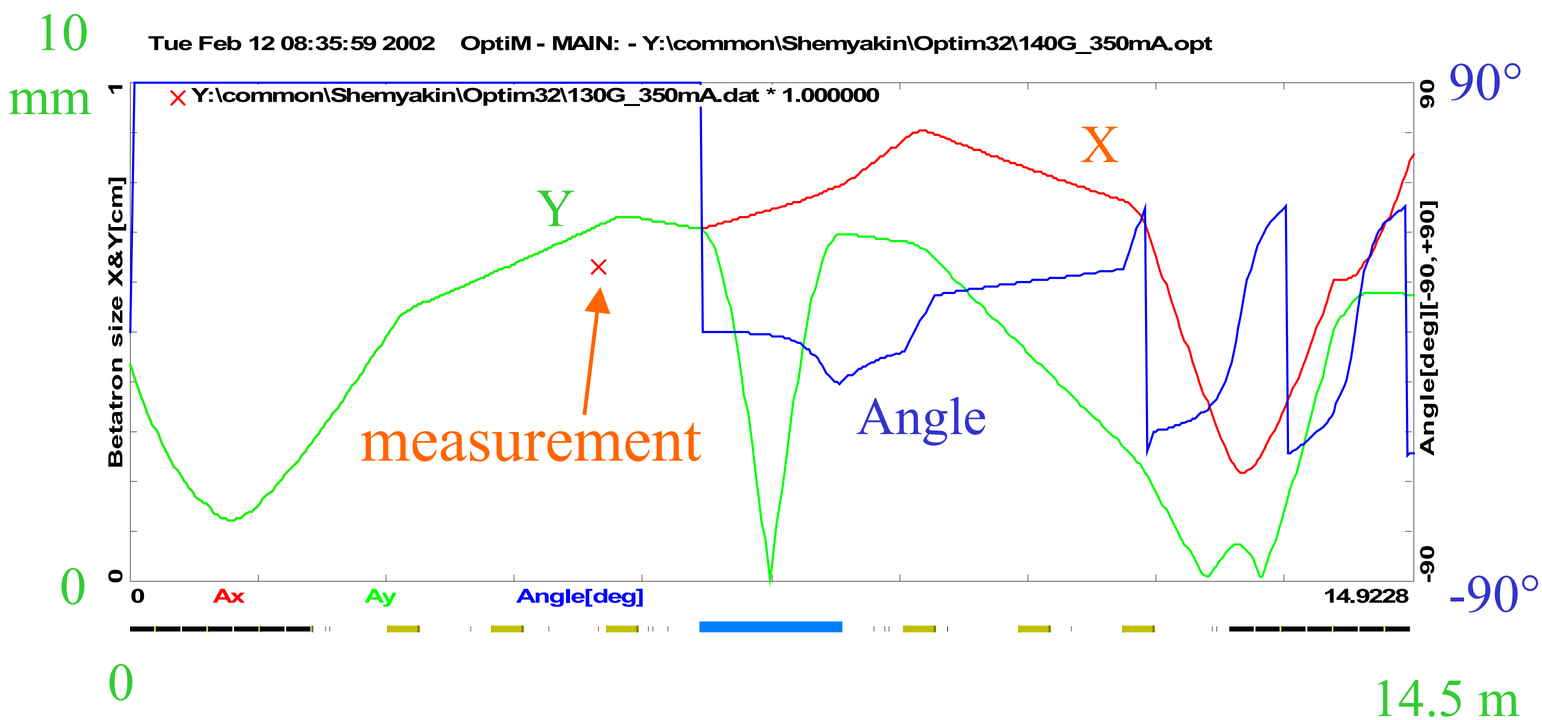
Simulation of the gun (SSAM) and low energy part of the acceleration tube (BEAM)





B_{cath} = 140 G, U_0= 3.5 MV, I = 350 mA, U_a= 25 kV.

Comparison of a beam size measurement and a simulation



B_{cath} = 140 G, U_0= 3.5 MV, I = 350 mA. Simulation is made by OPTIM32 with input data taken from SAM+BEAM.

Plans

We plan to finish the work with the short beam line in the spring of 2002 by demonstration of a stable operation at $I = 0.5$ A, $W = 3.5$ MV, $B_{cath} = 400 - 600$ G and to start working with a longer line in May'02 with a primary goal of testing the beam quality.

Who designed, built and commissioned the set-up

Fermilab:

A.Burov, A.C. Crawford, K.Carlson, V.Dudnikov, M.Frett, R. Hickey, R.Kellett, J. Klen, B.Kramper, T.Kroc, J.Leibfritz, A.Makarov, M. McGee, R. Moore, J.Nelson, S.Nagaitsev, S.Oplt, G.Saewert, J. Simmons, C.W. Schmidt, F.Saffrahn, A.Shemyakin, V.Tupikov, A. Warner, S.Wesseln

University of Rochester: S.Seletsky

National Electrostatics Corporation

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